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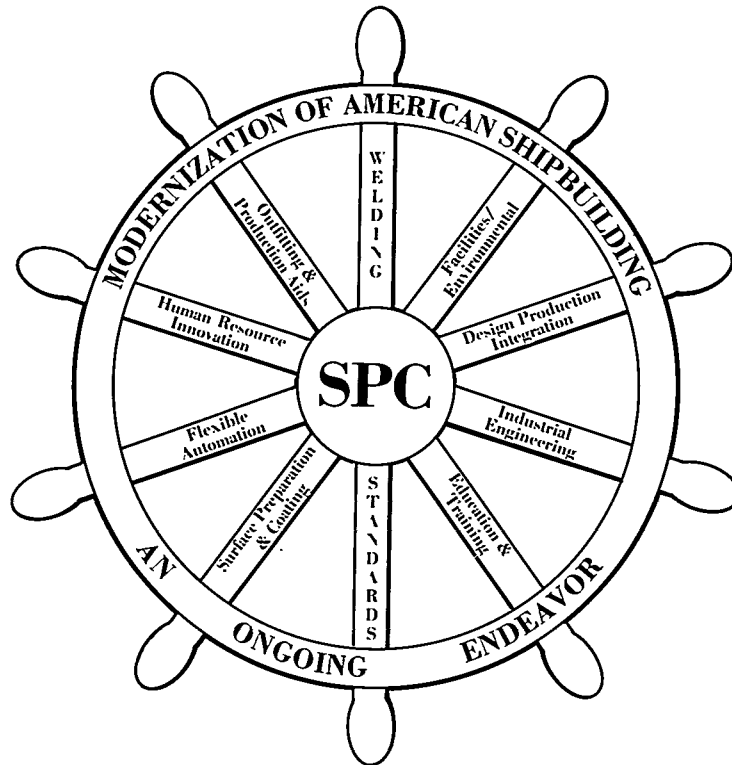
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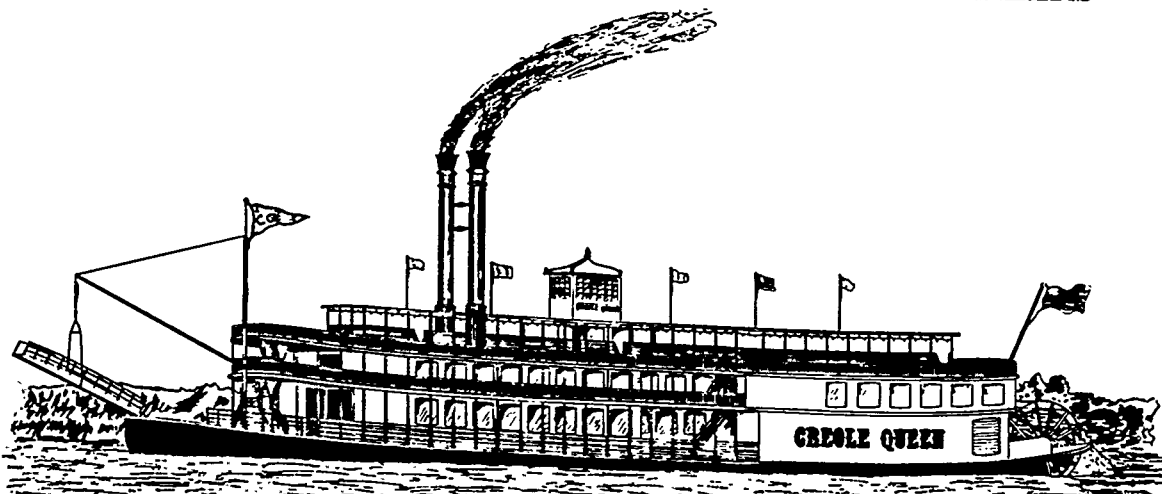
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The Use of Computer Simulation of Merged Variation to Predict Rework Levels on Ship's Hull Blocks

No. 4

R. L. Storch, Member, and P.J. Giesy, Student Member, University of Washington, Seattle, WA

ABSTRACT

In the modular construction of ships, significant productivity losses can occur during the erection stage, when the modules, or hull blocks, are joined together. Frequently, adjacent blocks do not fit together properly, and rework of one or both of the mating block interfaces is necessary to correct the problem. The specific cause of rework is the variation of plate edges at the block interface, which is itself a cumulative product of numerous manufacturing variations inherent in hull block construction. Variation in manufacturing is unavoidable, but not uncontrollable. The application of accuracy control techniques in shipbuilding has proven that a statistical analysis of variation makes possible an accurate prediction of its effects. This report presents an examination of block interface variation, and the subsequent development of a computer simulation method of predicting rework levels on those blocks.

The complex interaction of all the edges' random variations at the block interface gives rise to a unique rework probability distribution. This probability distribution is evaluated by means of the computer simulation program, which provides estimates of the average rework anticipated, the shape of the probability curve, and other parameters. Similar predictions are also available for cost and labor of required rework. In addition to predicting rework levels, the simulation program can be a useful tool for reducing those levels.

1. INTRODUCTION

Why Predict Rework?

A shipyard's need to predict rework is no different from its need to be in control of all other aspects of its operation. There are both short term and long term imperatives at work. The short term concern is the scheduling of the current project. It is necessary to have accurate forecasts of the time required for every work package in the project. The construction of a large vessel involves the coordination of thousands of work packages into a single, interdependent network of activities. If the duration of a job is overestimated, the result is an underutilization of resources. Scheduling inadequate time for a specific job, however, can disrupt the whole network. In the long term, a shipyard must direct attention to winning future contracts. A yard that knows its costs, including projected rework costs, is in the best position to bid realistically, and therefore successfully.

Rework is an intrusion on traditional construction schedules. Because it is an "unplanned" activity, there has been proportionally little effort invested in characterizing the rework function, compared to "regular" jobs. But rework can be a significant fraction of the total project. Quoting from Michael Wade of the University of Michigan:

"Regardless of how refined or standardized a planning system becomes, there is a high probability that during the life cycle of a ship construction

project, rework....will befall the production schedule with very little warning. It is unrealistic to plan vessel without consideration for the impact these disruptive factors can have on man-hours and completion dates....The ability to measure performance at all levels of production will have a direct effect on a shipyard's ability to bid new work consistently and confidently." [1] (emphasis added.)

2. THE REASONS FOR ERECTION STATE REWORK

Variation at The Block Interface

The cause of rework at the erection stage, neglecting design error, is variation at the block interface. Variation, in its formal definition, is a deviation from design dimensions. In an absolute sense, there is variation existing in every dimension of every item that has ever been manufactured; so long as an attribute can be measured closely enough, it can be found in deviation from what it is supposed to be. The question of practical concern is the magnitude of variation.

When two hull blocks are to be joined at erection, the critical dimension is the gap between the mating edges of the respective blocks. A uniform gap between all the edges at the erection joint allows the welding of the blocks - in many cases, robotic welding - to proceed as scheduled. Excessive variation of the edges of one or both of the block interfaces spoils this uniform weld gap and interrupts the erection schedule, as a certain percentage of the interface must be reworked to achieve a proper fit.

Specifications on weld joint preparation vary with the different types of welding, but there is in each case a gap tolerance, an upper limit and a lower limit on gap width, beyond which the quality of the weld suffers. As shown in Figure 1, when the weld gap is too narrow, or if there is interference between the plates, material must be removed by torch cutting from one or both sides. If the existing gap is too wide, a backing strip must be welded across the gap before the joining weld can be made.

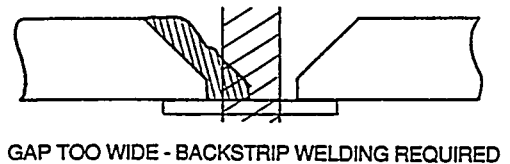
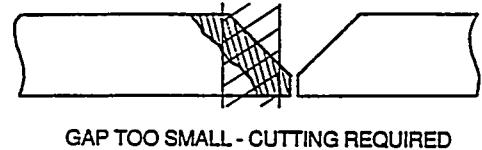
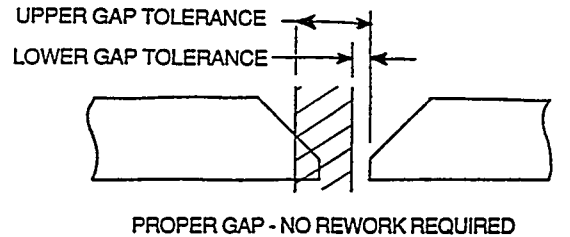


Fig.1. Rework Criteria - Cutting and Backstrip Welding

Of the two types of work, backstrip welding to close a gap is more expensive than torch cutting to widen one. Traditionally, shipbuilders, resigned to performing considerable rework at erection but anxious to minimize backstrip welding, would add a margin to part dimensions at the block interface to insure that, whatever the final block variation, a uniform gap could be achieved by cutting away from all the edges the portion of margin remaining. The practice is essentially a commitment to rework, and considering this, it is no surprise that erection stage rework levels at traditional shipyards are quite high. The use of margins may have been the minimum cost solution of the past, before the advent of statistical accuracy analysis, but times have changed. The application of accuracy control techniques is now permitting progressive builders to achieve much greater accuracy in hull block construction, making it possible to join hull blocks with less rework, and without margins.

Quantifying Variation

These same accuracy control techniques that make possible the reduction in block variation have an additional use as well. They can also be used to help determine how to deal most effectively with the variation that can not be eliminated. Through statistical characterization of the interface variation associated with a particular block design, it is possible to anticipate some of the consequences of that variation. Specifically, it is possible to make a prediction, before any steel is cut, on the amount of rework the block will require at erection.

Consider Figure 2, which shows a simple block interface and the variation of its edges. The design specifications of this hypothetical block are that the edges of all decks, bulkheads, and other members at the interface will lie on a single plane, as seen in Figure 2(a). However, due to variations of parts and processes in the construction of the block, each edge will exhibit some measurable variation from the design plane. Each edge's variation can be modeled separately as a random variable with a normal distribution. It is possible to

predict the random variations of each of these edges by writing a series of variation merging equations. Figure 2(b) represents the normal probability distributions of longitudinal variation of all the edges, with respect to the design plane (transverse and vertical variation can be evaluated as well, but not within the scope of this paper). These probability distributions are each characterized by a merged mean variation (Z_M) and a merged standard deviation (S_M). Note that some of the distribution curves are centered a little aft of the design plane and some are centered a bit forward. This illustrates a scattering of mean variations values above and below a value of zero.

A necessary precondition to the writing of variation merging equations is that all random part and process variations associated in the block construction be known, and known to vary under a normal distribution. A full description of the process of writing merging equations can be found in "Three Dimensional Accuracy Control Variation Merging Equations," by R.L. Storch and P. Giesy. A brief description of the principle of merging equations is provided by L.D. Chirillo:

"If the distribution of such variations for a specific work process is Gaussian, that is, normal per a bell-shape curve, the process is said to be under control. When work is so controlled, and verified daily by nominal random sampling, the normal distribution of a work stage can in accordance with the Theorem of Variance, be added to that for a second work stage in order to predict the distribution for a third work stage." [2]

It is impossible to predict exactly where a given edge will end up within its probability distribution. That is a random variable. Under a normal distribution, however, it can be said with fair certainty that the resultant positions will be within three standard deviations of the mean, within the so-called "six-sigma envelope." Figure 2(c) shows these six-sigma limits at the block interface. If 100 blocks were built from this design, they would all be different, but the configuration of each block interface will fall with certainty somewhere within that six-sigma

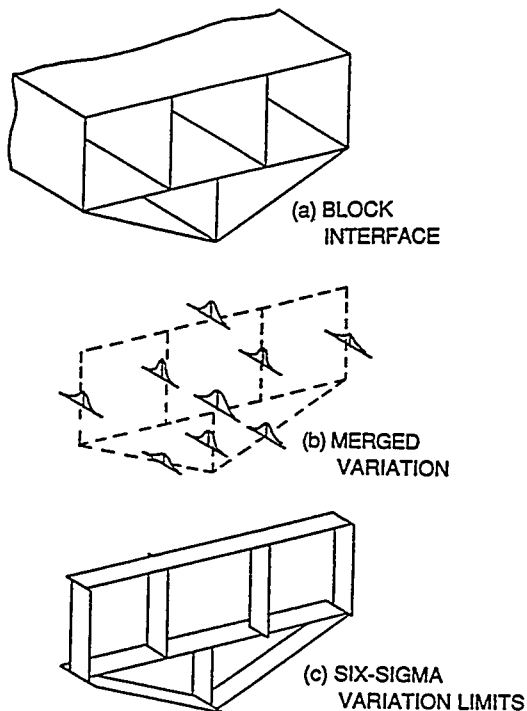


Fig.2. Longitudinal Variation of Edges at Block Interface

matrix. Knowing that variation at the interface is thus constrained, is the first step in the development of a method for predicting erection stage rework levels.

3. DEVELOPING A REWORK STRATEGY

Variation vs. Weld Gap Tolerance

It can be stated then, that erection stage rework is primarily a function of two opposing factors: the random variations of edges throughout the block interface, and the weld gap tolerance (there is a third factor, of course, called "economics," which will be incorporated presently). The greater the variation at the interface, and (or) the smaller the weld gap tolerance - the greater the probability that rework will be required; and expected levels of rework will be greater as well. Figure 3, which is a continuation of the hull block example started in Figure 2, illustrates this relationship. The two upper drawings show again the block interface and the six-sigma envelopes for all the edges. The diagram of variation limits at the bottom is simply a different representation of the six-sigma envelopes; it emphasizes the relative widths and longitudinal positions of the edges' variation limits. Since the relative lengths of the edges has been lost in the transition, that information is given in a column beside the diagram.

Note the cross-hatched area overlaying the variation limits in Figure 3. This represents the weld gap tolerance. As stated earlier, the weld gap throughout the erection joint must be between certain boundary values to avoid the necessity of reworking one or both edges of the gap. It does not matter what the upper and lower tolerance limits are, only the width of the tolerance zone is important. This visual comparison gives a feel for the probabilities of rework being required at the block interface.

To simplify the rework model being developed, this example will be presented as a case of one-sided variation. Under this constraint, manufacturing variations are present only on the block shown. The adjoining block is assumed to be "perfect," and therefore not a factor in determining rework requirements. Extension to the more realistic model of two-sided

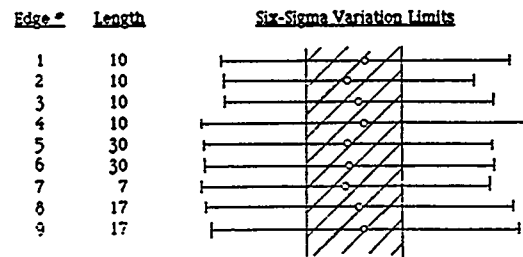
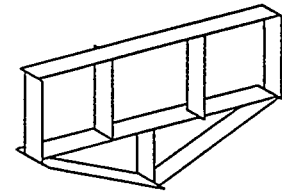
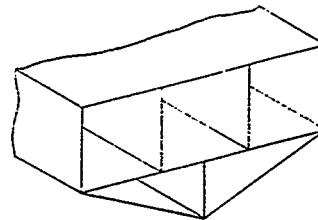


Fig.3. Diagram of Variation Limits

variation will be dealt with later. Simply stated, the rework criteria (with one-sided variation) is this: when the measured longitudinal span of plate edges at a block interface exceeds the weld gap tolerance, then rework is required. In the case of Figure 3, it is apparent that the variation limits are much wider than the weld gap tolerance. Intuitively, it is clear that the odds are very low of having these nine edges (effectively nine random variables) ending up in a zone smaller than the width of the weld gap tolerance. This is the same as stating a high probability that rework will be required at that interface.

The Optimum Rework Solution

But how much rework will be needed? Which edges will likely require cutting or backstrip welding? To answer these questions, it is necessary to examine the decision criteria of erection stage rework. The rework solution (which edges to cut, which to backstrip weld) for a specific block is dependent not only on the resultant longitudinal position of each edge after random variation has taken its toll, but on the

length of each edge as well. In each case, the problem becomes one of finding the optimum solution out of a set of feasible solutions.

To demonstrate this process of rework optimization, consider that our hull block from the previous examples has finally been built. Figure 4 shows the relative longitudinal positions of the nine edges at the interface. Maintaining the assumption of one-sided variation, the adjoining block can be represented as a flat wall, shown on the right. The shaded region near the wall represents the weld gap tolerance zone.

Finding the optimum rework solution can be viewed as an iterative thought experiment that is performed by moving the wall through the group of edges, stopping at each edge to calculate the implied rework for that case, and then selecting as the optimum solution the case requiring the minimum amount of rework. Since there are nine edges in our example, there are nine possible rework solutions: A, B, and C, shown in Figure 4, represent three of these. Solution A would be the first one evaluated. The wall is moved to the left until the first edge coincides with the minimum weld gap. At this position, the second edge is also within the tolerance zone, and so escapes rework. The remaining edges must be backstrip welded, for a total 114 feet of rework. Solution B is better than solution A. With the wall (actually the minimum weld tolerance) at the third edge, the first two need cutting and the last four need backstrip welding, for a total of 107 feet. Solution C, at 101 feet, is better than A or B. An evaluation of all nine solutions would confirm that C is in fact the optimum solution.

This example has represented a case where the unit costs of torch cutting and backstrip welding are equal. In actuality, backstrip welding is a more costly operation than cutting, and this affects the derivation of the optimum rework solution. The selection criteria changes from minimum rework to minimum cost. One would expect this to result in a shift, on the average, to somewhat higher levels of rework, but with a much smaller percentage of backstrip welding.

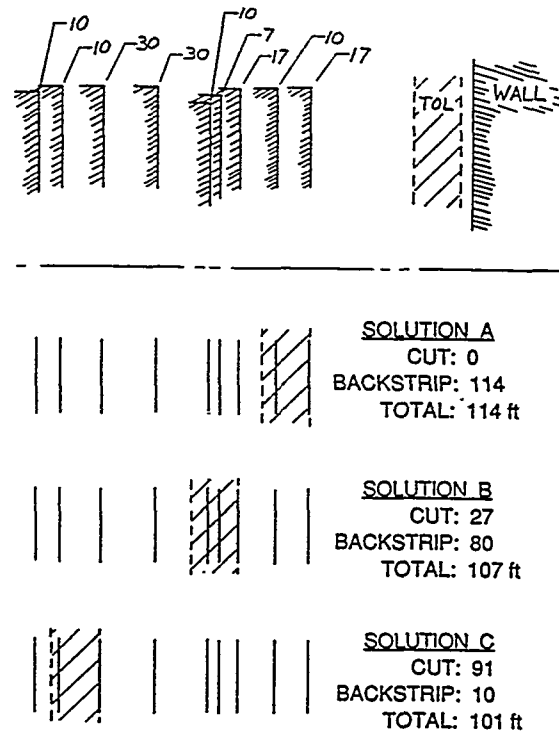


Fig.4. Rework Optimization

4. DETERMINING REWORK PROBABILITIES THROUGH SIMULATION

Estimating the Rework Profile

It has been established that the optimum rework solution is a function of edge variation, edge length, the weld gap tolerance, and rework costs. The only problem remaining is the one that we began with, that of how to predict the amount of rework that a given block design is likely to require. It is a problem that does not lend itself to an analytical solution. Though edge lengths, weld tolerance, and costs are all constants, and the variation distribution of each edge is characterized by a mean and a standard deviation, the complex interaction of those random variations, influenced by all of the constants, defies expression.

But analysis is not the only method available. Much can be said about rework. Since rework is a function of random events, it is itself a random variable, and can be represented as a probability distribution of optimum solutions. It is not a continuous distribution, since it cannot take

on a continuous range of values. The values that rework can take are constrained to the finite set of all possible combinations of sums of edge lengths.

This type of problem is best solved through statistical modelling. In other words, using empirical methods, rather than analytical. The most straightforward method would be to sample a large number of hull blocks built from the same design, and generate statistics, such as average rework and standard deviation, to describe the rework distribution. Sampling is a valuable statistical tool, which has already played an important role earlier in this chain of analysis: it was sampling that was used to determine the parameters of the specific shipyard process variations. And the process variations, of course, are what the distributions of merged variation of edges at the interface are derived from. Sampling of hull blocks, however, would appear to defeat the purpose of predicting rework prior to construction - unless a computer was used to generate the sample. The following section describes a computer program written for such a purpose.

The Rework Simulation Program

With a rework simulation program, it is possible to "build," and evaluate for rework, many hull blocks at no cost and in very little time. And many hull blocks will be needed. If optimum rework was known to have a normal distribution, then a mean and standard deviation could be inferred from as few as ten or twenty observations. But since the shape of the rework distribution is not (yet) well defined, the profile must be "constructed" as a histogram of a large number of observations. This program estimates the rework profile with a histogram derived from two hundred simulated hull blocks.

The program described here is written in Pascal, and runs on an Apple MacintoshTM personal computer. The Macintosh has excellent graphics capabilities, and the mouse-interface enhances the "friendliness" of the program. A complete listing of the program is given in the appendix.

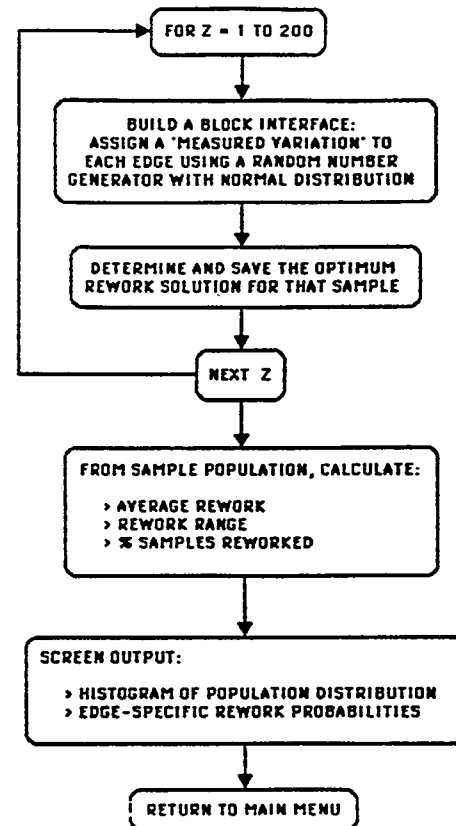


Fig.5. Simulation Subroutine Flowchart

The mechanics of running a simulation are outlined in Figure 5. For each sample hull block, a "resultant variation" is assigned to each edge at the interface using a random number generator that complies with the normal distribution of merged variation of that edge. The algorithm for this is as follows:

First, a random number (N) with a [0,1] normal probability distribution (i.e., mean = 0, standard deviation = 1) is generated with the equation:

$$N = (-2 \log_e R_1)^{1/2} \cos(2\pi R_2)$$

where R_1 and R_2 are uniform distribution random numbers from 0 to 1.

Then, the "resultant variation" for the j^{th} edge is:

$$Z_j = \bar{Z}_j + (N * S_j)$$

where \bar{Z}_j and S_j are the edge's merged mean variation and standard deviation, respectively.

A new "N" is generated for each edge.

After each block interface is created in this manner, the program then determines that block's optimum rework solution, using a preselected weld gap tolerance and costs of torch cutting and backstrip welding. The optimum solution, chosen on the basis of minimum cost, is recorded in terms of total linear feet of rework, irrespective of type. At the same time, a cumulative counter (over the 200 samples) makes note of the specific edges that required rework, and which type.

This whole procedure is repeated two hundred times to simulate the construction and rework of the entire sample of hull blocks. The two hundred optimum rework values become the raw data that are used to estimate the rework distribution. The rework mean and standard deviation are calculated from the sample data, and the shape of the distribution curve is approximated by a histogram of the data.

A full flowchart of the program is shown in Figure 6. On startup, the user must load a block variation table (either by hand, or from a file) into the program memory. This variation table lists

the names, merged mean variations, and standard deviations of all the edges at the block interface, and their respective lengths. The program then proceeds to the main menu, where the user may choose to run a simulation, display or edit the variation table, or end the program. After each simulation, the user can call to the screen, or print, four different graphical reports: the Rework Distribution, Cost Distribution, Labor Distribution, or Edge Specific Rework Probabilities.

5. A CASE STUDY: THE T-AGOS REWORK PROFILE

An Introduction to The T-AGOS Case

In 1983, R.L. Storch produced a paper called "Accuracy Control: A Guide to its Application in U.S. Shipyards" [3], which was based on research that had been done at the University of Washington and at the Tacoma Boatbuilding Co. in Tacoma, Washington. The main purpose of that research was to outline the procedures for determining typical shipyard process variations and constructing variation merging equations. A major project then at Tacoma Boat was a Navy contract to build a series of twelve T-AGOS class ocean surveillance vessels.

Three years later, in "Three Dimensional Accuracy Control Variation Merging Equations" [4], Storch and Giesy wrote a series of merging equations, characterizing the merged longitudinal variation of all edges at the erection interface of a specific hull block: the T-AGOS stern section. A full list of the edges at the stern block interface is given in Figure 7.

This complete collection of block interface variation parameters provides a realistic data set to run through the simulation program. However, it is first necessary to explain an additional complication in the T-AGOS variation table that was not covered earlier.

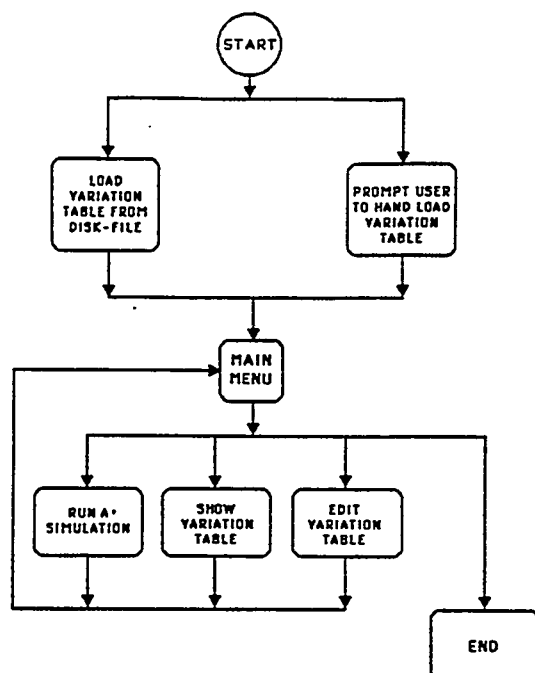
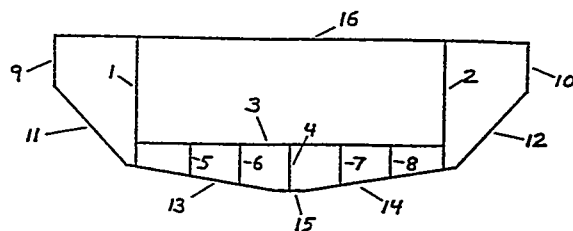


Fig.6. Rework Simulation Program Flowchart



Edge #	Name
1	Longitudinal Bulkhead (stbd)
2	Longitudinal Bulkhead (port)
3	13'6" Steering Gear Flat
4	Centerline Floor Frame
5	Diagonal Floor Frame (1)
6	Diagonal Floor Frame (2)
7	Diagonal Floor Frame (3)
8	Diagonal Floor Frame (4)
9	Side Shell (stbd)
10	Side Shell (port)
11	Bilge Strake (stbd)
12	Bilge Strake (port)
13	Bottom Shell (stbd)
14	Bottom Shell (port)
15	Keel Plate
16	Main Deck

Fig.7. Summary of T-AGOS Stern Block Interface

Independent vs. Relation Variation

The T-AGOS variation table is shown in Table 1. Note the appearance of a factor called "Mutual Variation" associated with some of the edges. This indicates the presence of the phenomenon of Related Variation, revealed through the writing of the variation merging equations. Edges 3 through 8 are a group of edges whose merged variations are related; they will be said to comprise Related Group #1. Likewise, the Main Deck, originally seen as one continuous edge, is more accurately represented as five shorter edges with related variation, making up Related Group #2. The variation of an edge in a related group is characterized by a random independent variation and also a random mutual variation that is common to every edge in that group. The rework simulation program must be able to take occurrences of related variation into account to realistically predict rework on hull blocks that contain these related groups.

Table 1. T-AGOS Variation Table

T-AGOS - VARIATION TABLE				
Edge #	Name	Length (ft)	Independent MeanVar / StndDev	Mutual MeanVar / StndDev
1	Long'l Bhd (stbd)	8.00	-0.220/0.260	---
2	Long'l Bhd (port)	8.00	-0.220/0.260	---
3-1	13'6" Flat	26.00	-0.020/0.220	-0.160/0.250
4-1	Centerline Frame	2.50	-0.020/0.220	-0.160/0.250
5-1	Diag. Frame (1)	1.75	-0.020/0.200	-0.160/0.250
6-1	Diag. Frame (2)	2.14	-0.020/0.200	-0.160/0.250
7-1	Diag. Frame (3)	2.14	-0.020/0.200	-0.160/0.250
8-1	Diag. Frame (4)	1.75	-0.020/0.200	-0.160/0.250
9	Side Shell (stbd)	3.60	-0.060/0.180	---
10	Side Shell (port)	3.60	-0.060/0.180	---
11	Bilge Strake (stbd)	6.60	-0.060/0.180	---
12	Bilge Strake (port)	6.60	-0.060/0.180	---
13	Bottom Shell (stbd)	14.25	-0.080/0.260	---
14	Bottom Shell (port)	14.25	-0.080/0.260	---
15	Keel Plate	1.60	-0.080/0.260	---
16-2	Main Deck (1)	8.00	-0.010/0.170	-0.170/0.210
17-2	Main Deck (2)	8.00	-0.010/0.170	-0.170/0.210
18-2	Main Deck (3)	8.00	-0.010/0.170	-0.170/0.210
19-2	Main Deck (4)	8.00	-0.010/0.170	-0.170/0.210
20-2	Main Deck (5)	8.00	-0.010/0.170	-0.170/0.210

The explanation of Group 1's related variation is found in the internal structure of the T-AGOS stern block. Figure 8 shows a partial exploded view of the block. The location of the block interface is at station 96, where the forward edges of the 13'6" flat, the centerline frame, and the four diagonal frames are seen to lie. The merged variation of these edges (and of all the other edges at the interface) are calculated with respect to bulkhead 100. The exploded view shows the 13'6" egg box abutting the 15' egg box, and the 15' egg box in turn abutting bulkhead 100. The forward transverse of the 15' egg box (at station 96) therefore determines the position of the 13'6" egg box. The location of this transverse frame, however, will have variation with respect to bulkhead 100, variation that will affect equally the variation of the edges at station 96. This, then, is the mutual variation that is shared by all edges in related Group #1. The edges' independent variations come from process variations that occur forward of station 96.

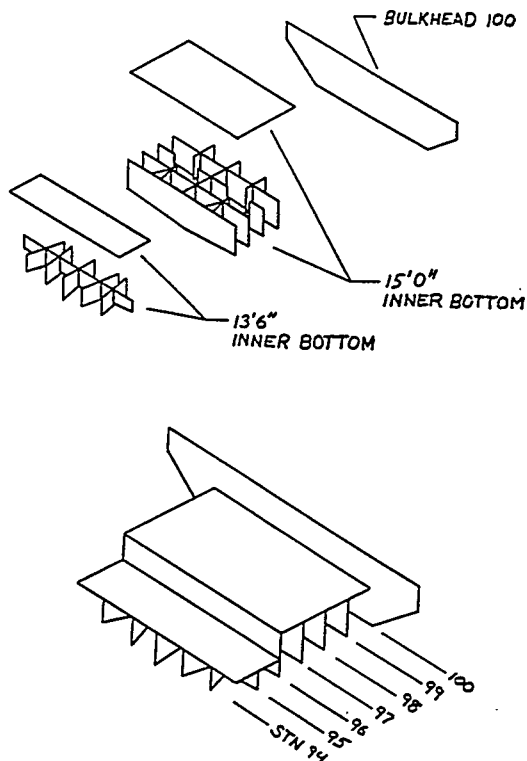


Fig.8. T-AGOS Stern Section - Exploded View

The reason that the Main Deck was subdivided into a related group is because of its assembly sequence. The Main Deck is originally assembled from five flat panels, running fore and aft. There is variation associated with the construction of these five panels that will manifest itself independently for each panel. After the panels are joined, however, they constitute the Main Deck, and its installation onto the hull block results in additional variation that is mutually experienced for each of the five previously separate edges.

When variation tables with related groups, such as the T-AGOS table, are loaded into the rework simulation program, both mutual and independent variation are randomly generated to represent the "construction" of the two hundred hull blocks. The following section presents the program's estimate of rework for the T-AGOS stern block, and a sensitivity analysis to evaluate options on improving it.

The T-AGOS Rework Profile

The probability of rework on the T-AGOS stern section will be assessed in terms of the labor required instead of by the actual linear feet of rework (cutting and backstrip welding) at the interface. A focus on rework labor can be an equally effective method of monitoring accuracy performance, and projections of labor requirements are more useful for purposes of scheduling the build sequence. The simulation program evaluates rework labor by allocating predetermined man-hour rates (per unit length), for cutting and backstrip welding, to the optimum rework solutions generated in the simulation.

For the T-AGOS simulation, a labor rate of 0.25 man-hours per foot for cutting and 0.58 man-hours per foot for backstrip welding will be used. These are hypothetical values, and do not imply standards of welding performance at Tacoma Boat or any other shipyard. This represents a ratio of labor rates of about 2.3, and since labor constitutes the major element contributing to total rework costs, a cost ratio of 2.5 will be used to determine the optimum rework solutions.

Figure 9 shows the distribution of rework labor for two separate runs of the simulation program. Both profiles are skewed to the right, though there are differences in the details. The mode of the upper profile is at approximately 28 man-hours, while that for the lower profile lies at around 24

man-hours. The labor averages, however, differ by only about 2%, at 22.7 and 22.2 man-hours, respectively. If a better approximation of the true distribution is needed, it can be had by taking a greater sample size in the simulation.

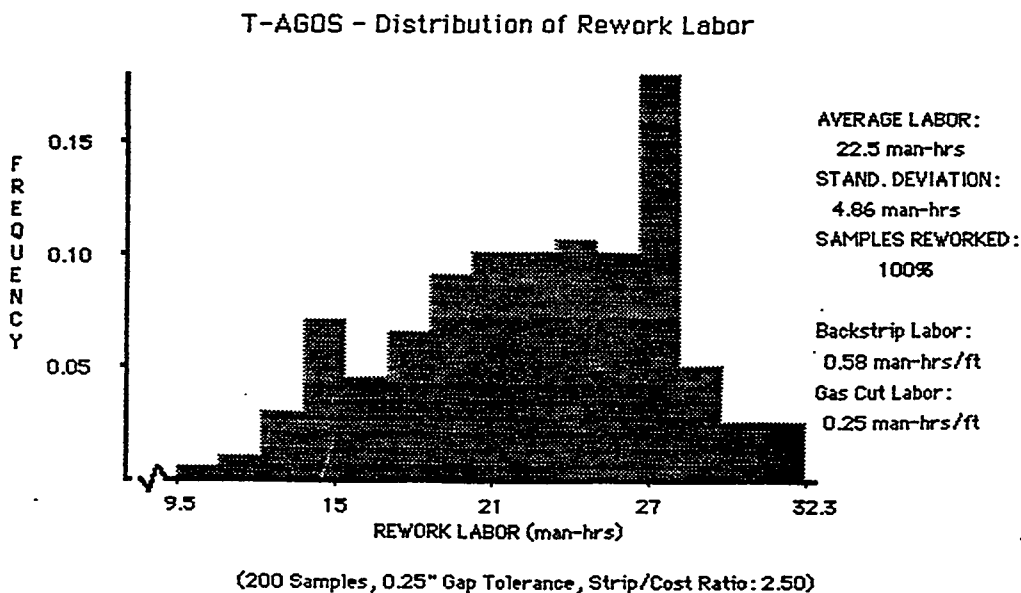
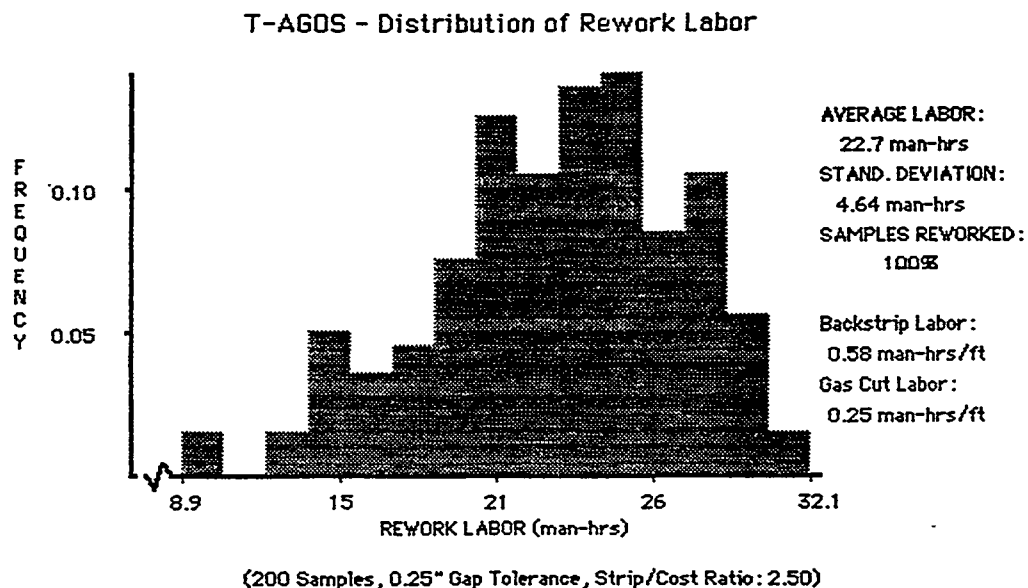


Fig.9. T-AGOS Labor Profiles from Two Separate Simulation Runs

Having obtained an estimate of the anticipated rework on the T-AGOS stern block, the next step is to run a few more simulations to observe how certain design changes will affect the profile. The first axiom of quality control is the importance of reducing variability. In the T-AGOS case, there are several ways of approaching the problem. Figure 10 is the diagram of variations limits for the edges at the block interface (these limits come directly from the variation table in Table 1). The figure shows that the edges in related group #1 - the 13'6" Flat, and the Centerline and diagonal frames - exhibit the greatest amount of variation, while the forward edges of the side shells and bilge strakes have the least variation. A reduction in these variation limits would certainly reduce variability. But since these are merged variations, this implies the need for either a

in Figure 10 in the misalignment of the six-sigma variation limits. Lining up the variation limits is accomplished by normalizing all of the mean variations to a single value. A merged mean variation can be changed by simply introducing an "engineering variation" somewhere in the build sequence - by, for instance, telling the N.C. cutting machine to cut out a plate that is slightly longer than called for in the drawing. This would change the mean variation at the block interface without affecting the standard deviation.

This strategy was tried out on the simulation program. The T-AGOS variation table was edited to bring all of the edges' mean variations to zero, and the new table designated "T-AGOS(zero)." The results, given in Figure 11, show a reduction in average rework labor, but not by much. The improvement amounts to something between 2% and

T-AGOS - VARIATION LIMITS

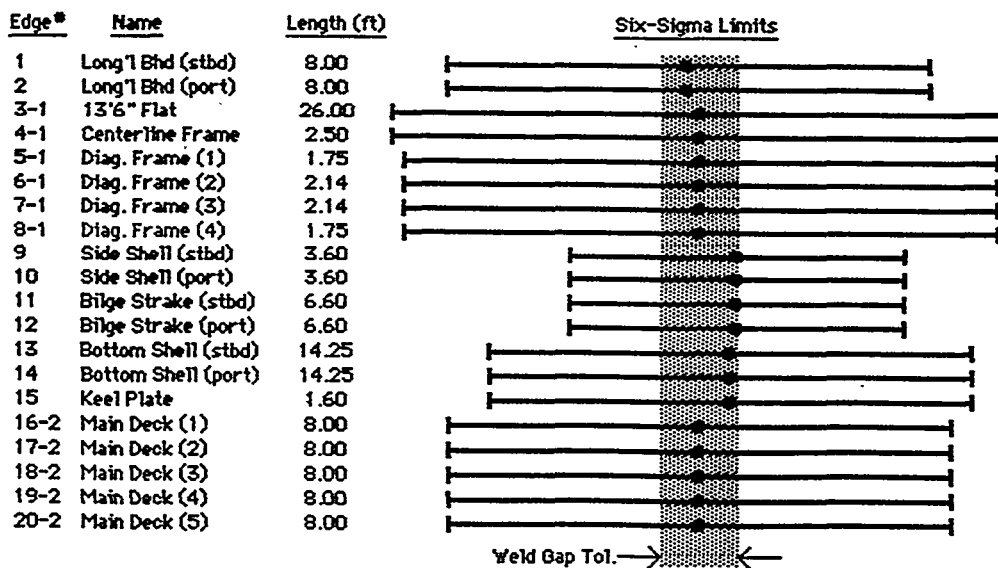


Fig.10. T-AGOS Variation Limits

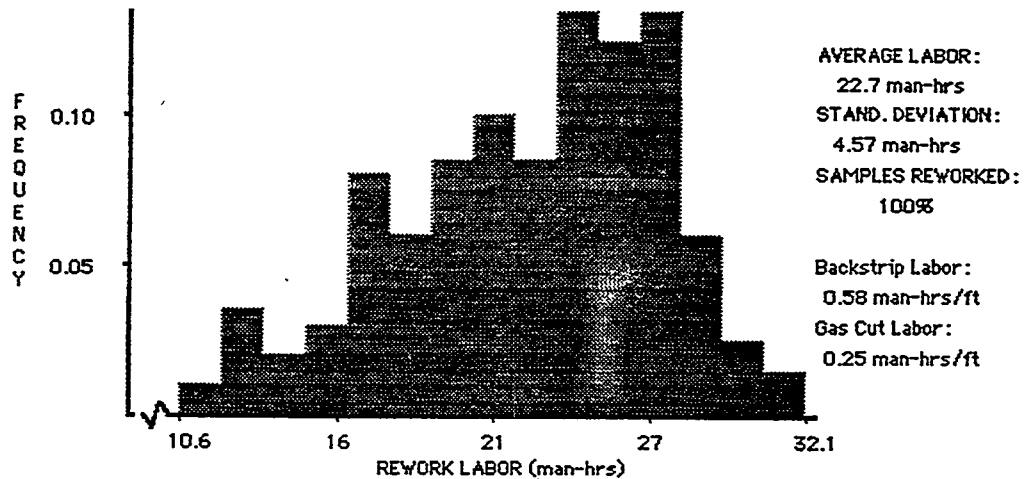
different assembly sequence or a reduction in the process variations throughout the shipyard; neither of which might be immediately available to the engineering staff.

The case does present, however, an element of variability that can be very easily dealt with, and this is that the merged mean variations of the edges at the interface are not all the same. This is evident

4% of the original average. Clearly, there is still much improvement to be gained through a reduction of merged standard deviations.

To evaluate the effect of a general reduction in standard deviation, two more simulations were run. The two new variation tables are called T-AGOS(90%) and T-AGOS(80%), reflecting an overall

T-AGOS(zero) - Distribution of Rework Labor



(200 Samples, 0.25" Gap Tolerance, Strip/Cost Ratio: 2.50)

Fig.11. T-AGOS(zero) Labor Profile

reduction (from the original T-AGOS) of all the edges' merged standard deviations by 10% and 20%, respectively. The results are shown in Figure 12. The 10% and 20% reductions in standard deviation produce around 5% and 9% reductions in average rework labor.

It is difficult, and probably of little value, to try to compare these two different approaches to reducing variability. Going from a T-AGOS to a T-AGOS(zero) is very simple, once the merged variations are understood, but the benefits are limited. Getting from a T-AGOS to a T-AGOS(90%) may take many years of Accuracy Control work, but ultimately there is much more potential for economic reward along that path. Even though it all falls under the heading of Accuracy Control, it appears that accuracy is relatively easy to achieve - it's precision that takes a lot of work.

6. STEPS TOWARD PRACTICAL APPLICATION

Sections 1 through 4 have been devoted to developing a model of merged variation at the block interface, explaining the decision criteria for performing rework on the interface, and introducing and testing a simulation program written to predict the rework outcome on a given hull block, based on the assumptions in the model. The program is shown to be

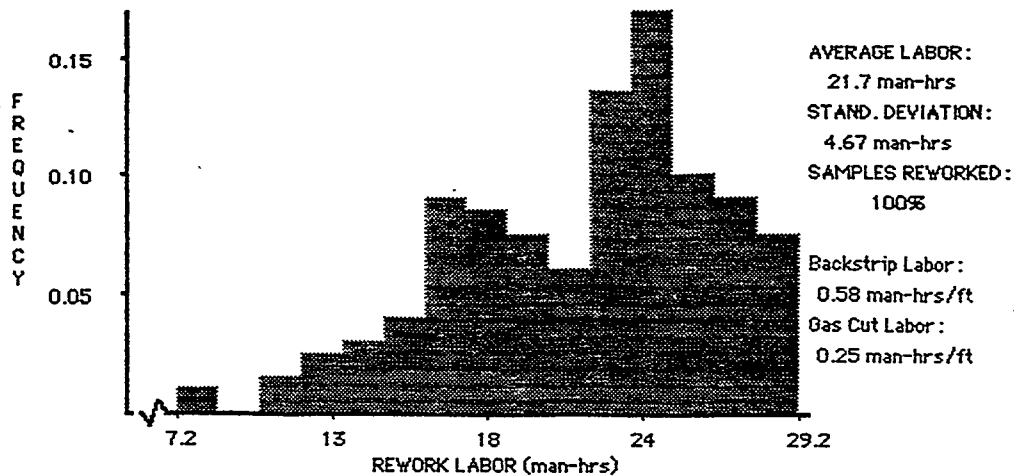
capable of producing useful output. Its graphical representations of the rework, cost, and labor distributions are easy to interpret, giving the user a good grasp of the probabilities associated with easy case.

Given all this, however, the program is still not ready for service in a real application. The variation/rework model presented here contains several major simplifications, as is appropriate in early stages of research, which need to be addressed before the program is finally ready for use. This section presents a brief discussion on some of these remaining issues, and sketches out what work is left to be done for the refinement of the model and the implementation of the simulation program

Choosing an Effective Sample Size

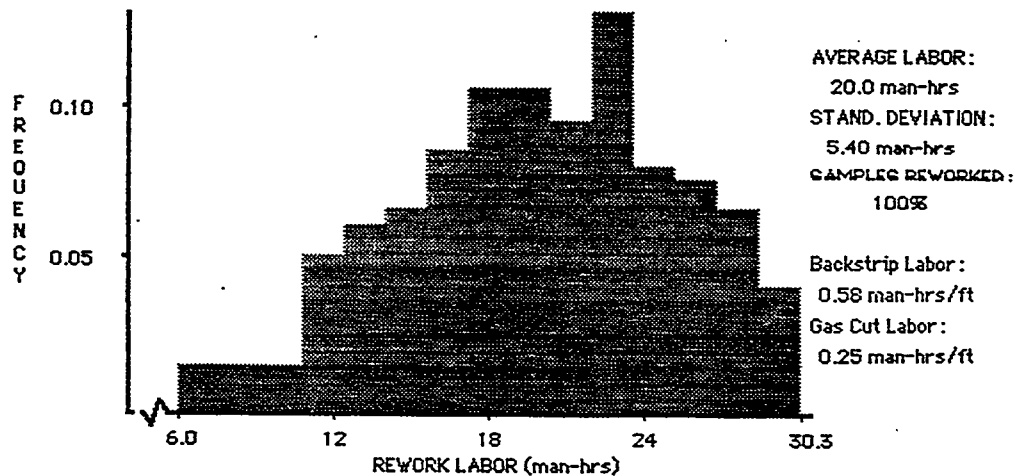
At several points in this report, the axiom, "the bigger the sample, the better the approximation," has been used to acknowledge the topic of sample size. The sample size of two hundred hull blocks, used in these simulations, was chosen fairly arbitrarily. It is necessary, however, in an industrial application, to address more specifically the questions of "how much" versus "how good," because the decisions have an economic consequence.

T-AGOS(90%) - Distribution of Rework Labor



(200 Samples, 0.25" Gap Tolerance, Strip/Cost Ratio: 2.50)

T-AGOS(80%) - Distribution of Rework Labor



(200 Samples, 0.25" Gap Tolerance, Strip/Cost Ratio: 2.50)

Fig.12. T-AGOS(90%) and T-AGOS(80%) Labor Profiles

How good will a prediction of average rework be for a given sample size? Actually, the quality of the prediction depends not only on sample size, but also on the profile and standard deviation of the population. Statistically, the best way to answer this sort of question is in terms of a confidence interval. A confidence interval is an interval, centered

about the sample mean, within which it can be stated (at a certain level of confidence) that the population mean lies. A 95% confidence interval implies a 5% chance of error, or an "alpha error" of 0.05.

Assuming that the rework profile is a normal distribution (which it isn't), then it is a simple matter to calculate confidence intervals. The formula is:

$$\bar{X} - (S/\sqrt{n})Z_{\alpha/2} < \mu < \bar{X} + (S/\sqrt{n})Z_{\alpha/2}$$

where :

μ =population mean

\bar{X} =sample mean

S=standard deviation

n=sample size

$Z_{\alpha/2}$ =the standard normal value with an $\alpha/2$ probability.

Applying this formula to the first T-AGOS simulation, with a sample mean of 22.7 man-hours and a standard deviation of 4.45, a 95% confidence interval is calculated to be: 22.7 ± 0.62 man-hours, or $22.08 < \mu < 22.32$. The width of the confidence interval is about 5% of the value it constrains. Table 2 lists 95% confidence intervals for the T-AGOS case for sample sizes of 50, 100, 200, and 500. Since the rework function is not a normal distribution, these are only rough estimates, but they provide at least a basis for comparing the size of the simulation with the accuracy it delivers.

Table 2. Confidence Intervals for Various Sample Sizes

Sample Size	95% Confidence Intervals (man-hours)
50	$\bar{X} \pm 1.23$
100	$\bar{X} \pm 0.87$
200	$\bar{X} \pm 0.62$
500	$\bar{X} \pm 0.39$

Characterizing Merged Variation in Three Axes

In this paper, fluctuations in the erection weld gap have been attributed to merged variation at the block interface only in the longitudinal direction. Obviously, a constructed hull block will experience some variation along the transverse and vertical axes as well, affecting the weld gap, and consequently rework. This would

seem to imply that three orthogonal sets of variation merging equations must be written for each edge at the interface to fully characterize its impact on the rework function. A simulation program could certainly be written to accommodate this, though at some point, the added complexity of the calculations may render the program unworkable on a mere personal computer.

It's possible, however, that such complete characterization is not always necessary. An edge's contribution to the rework function might be found to consist of only two factors: its longitudinal variation, and its perpendicular variation. For instance, in the case of a vertical bulkhead, the longitudinal and transverse variations are the only relevant factors; any vertical variation encountered will not affect the weld gap. Likewise, for a horizontal deck, only its longitudinal and vertical variation might need be considered. The variation of obliquely angled edges would have to be characterized in all three directions, but even this case can be resolved to just longitudinal and perpendicular variation through a rotation of coordinate axes. Curved edges, unfortunately, are not amenable to any of this rationalization.

The nature of the erection weld joint might also have a bearing on how many axes of variation must be addressed. This brings the adjoining block into consideration. If a weld joint is edge-to-edge, then the play (or rather, the interplay) of both longitudinal and perpendicular variation will determine the weld gap. Depending on welding technology, rework criteria may either remain in terms of overall weld gap tolerances, or depend on the interrelated result of a longitudinal gap and a planer gap. On the other hand, if an edge on the first block is to be welded to the face of a bulkhead on the second, then the edge's perpendicular variation is not a contributing factor to the quality of the weld joint (though, granted, it may be of great concern to the American Bureau of Shipping's strength requirements).

Considering Two-Sided Variation

Since the "adjoining block" has entered the discussion again, it is an appropriate time to talk about another shortcoming of our present variation/rework model. As it

stands now, the simulation program assumes a model of one-sided variation, that is, variation on only one of the blocks at the erection joint. But in reality, variation from both of the blocks will actually determine the rework function. There are two ways that this can be addressed.

The first method is to revise the rework program to simulate the variation at the interface of both of the blocks. Two variation tables would be loaded into the program instead of one, and the simulation would begin by "building" two hundred blocks of the first type and two hundred of the second. Determination of the optimum rework solution of each case would in principle be the same as before, but would necessarily account for the variation on both sides of the weld joint. Instead of moving a flat plane through the interface of the one block, and evaluating in turn each possible rework solution encountered, one block would be moved through the other, with the coincidence of each pair of mating elements representing a possible rework solution. At each out-of-tolerance joint, it would be immaterial which of the two edges actually received the rework. The optimum solution would still be the one that incurred the minimum cost. The subroutine to perform this task would be more complex than the one in current use, but still within the scope of a competent programmer.

A second method for modeling two-sided variation would, as opposed to the first, require no revision of the current program, and should yield an equivalent solution. The plan involves "merging" the merged variation of mating elements at the interface to create a "two-sided variation table" that can be processed by the current, one-sided model. This can also be described as the action of "folding," or transferring, the variation of the second block onto the first block, thereby maintaining the model of one-sided variation. If an edge on one block has a mean variation of 0.25" and a standard deviation of 0.20", and its mating edge on the other block has a mean variation of -0.25" with a standard deviation of 0.30", then the combined effect would correspond to a one-sided mean variation of zero, with a standard deviation of 0.36".

Assuming that the second proposed method is equivalent to the first, it would accomplish the same task with much less computational effort. The reasoning seems intuitively sound, but at this time, a formal proof of the equivalence cannot be presented. The most straightforward test would be to write two parallel simulation programs, one for each method, and compare the results.

Using Feedback to Improve The System

No matter how complex the model becomes, it will always remain just an approximation of real life. Unforeseen factors, or inaccurate representation of chosen factors, can bias the results of the simulation. This is not to imply that the simulation program cannot be a valuable tool, but it does suggest a strategy for further improving the quality of the program's output. Once the system is in place, recorded rework can be compared to the program's predictions, to characterize the overall accuracy of the model. The concept is similar to the analysis of residuals in a designed experiment.

The error of each prediction - that is, the difference between the projected and actual values - can be determined for every erection joint. If the predicting errors are normalized to (for instance) a percentage of the actual outcome, then they can all be plotted together to detect possible trends. The rework prediction for one interface might be 10% high; for the next interface, it might be 6% low. If there is no bias in the model, then the average error will be zero. If the model does contain bias, then future simulation results can be amended to compensate for the average percentage error, and achieve a more accurate prediction. The monitoring of error can also lead to an improvement of the model itself, if it can point out specific inaccuracies in the current assumptions. The goal of a continuously improving manufacturing system is facilitated in part by a continuously improving control system.

7. CONCLUSIONS

The purpose of this report has been to show the capabilities of computer simulation in predicting rework on ship's hull blocks at erection. This simulation of the rework function is made possible because of two very powerful concepts that have effected great changes in shipbuilding technology over the last few decades. These are Group Technology Manufacturing and Statistical Process Analysis. Group technology promotes the rational organization of a large project into categories of similar work packages, shifting focus from the building of ships to the building of interim products. Statistical process analysis gives the shipyard a direct understanding of its own manufacturing capabilities, and at the same time, a practical framework for continuously improving those capabilities.

This greater element of control in shipbuilding technology permits a characterization of the factors that lead to erection-stage rework. Random block variation at the erection interface is modeled through the writing of variation merging equations. Rework for a given hull block design is the function of this random variation, as well as several fixed factors. All of these factors can be represented in a computer simulation. This report demonstrates the use and usefulness of the author's simulation program by applying it in the context of a case study. The significant findings from the variation and rework studies, as well as the simulation results, are summarized below.

1. Rework on hull blocks is performed to rectify the effects of variation of the edges at the block interface. The specific goal of rework is to create a uniform weld gap at the erection interface by bringing all of the edges into the same weld tolerance zone. When considering a given constructed block, there are many rework solutions through which the interface can be made acceptable. The optimum rework solution is the one incurring the minimum cost, based on the four-way interaction between the resultant variation of the block's various edges at the interface, the lengths of the edges, the weld gap tolerance, and the relative costs of rework.

2. As merged variation at the block interface occurs randomly, the optimum rework solution is itself a random variable, having a unique probability distribution profile. The rework simulation program, by modelling all of the factors listed above, can sample from the "population" of hull blocks and generate an estimate of the rework distribution to any accuracy desired. The program also produces estimates of the rework cost and labor profiles, and the rework probabilities of the specific edges at the interface.

3. The characterization of the rework function can be very useful when writing schedules and budgets for the erection stage of construction. The forecasts for each of the ship's blocks can be assessed during the design phase to look for blocks with high rework probabilities, where design changes might be needed. The estimate of edge specific rework probabilities can identify when certain edges are contributing an excessive amount to rework levels at the interface. Such early detection of potential problems can help the shipyard to avoid costly disruptions in the building schedule.

4. Overall projections of rework levels for the entire ship can be obtained by summing the individual block projections. The management can use overall projections to evaluate the producibility of the design, and the product's acceptability with respect to the buyer's expectations. Preliminary projections may indicate a likelihood of cost or schedule overruns, in which case, negotiation can be initiated as early as possible to reach the most satisfactory outcome.

5. In addition to its value in costing and scheduling, the simulation program can also be an important tool for increasing productivity. The program can be used to assess the impact of proposed process improvements, such as greater precision of certain manufacturing operations, or an increase in weld gap tolerance. With this information, operations spending can be prioritized to yield the greatest impact for the dollar.

The program presented here is just a demonstration model. Every shipyard that elects to make use of such a program will incorporate into it the characteristics of those fabrication and rework practices that are unique to that yard. It should evolve and improve, in reflection of the shipyard itself, becoming a valuable asset to future production capabilities.

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